Reply to the Comment on "A Precise Determination of Electroweak Parameters in Neutrino-Nucleon Scattering"

In a recent comment [1], Miller and Thomas correctly indicate that if nuclear shadowing effects differed significantly between neutrino neutral current (NC) and charged current (CC) interactions, this difference would impact NuTeV's measurement of $\sin^2\theta_W$. As motivation, they offer a specific vector meson dominance (VMD) shadowing model [2] and argue that nuclear shadowing within the VMD model is weaker for Z^0 exchange than for $W^\pm$ exchange [3], thereby increasing the predictions for R^ν and $R^{\overline{\nu}}$ for a portion of the NuTeV data in the low Q^2 shadowing region. This effect of VMD models, though, has the *wrong sign*, since NuTeV measures ratios for neutrino and antineutrino scattering processes, $R^\nu_{\rm exp}$ and $R^{\overline{\nu}}_{\rm exp}$, that are both smaller than expected. Furthermore, this class of models in general and the specific model offered, both fall well short of providing an explanation for the NuTeV observations for a number of reasons.

First, shadowing by VMD is not supported by charged-lepton deep inelastic scattering (DIS) data in the relevant kinematic regime. The VMD model can be tested by looking for deviations from logarithmic Q^2 dependence of shadowing, particularly at low Q^2, where VMD models would predict a Q^2 dependence of the form $1/(Q^2+m_V^2)$, m_V being the mass of the vector meson. The most precise data which overlaps NuTeV's kinematic region (97% of the NuTeV data is contained within $1<Q^2<140$ GeV^2, $0.01<x<0.75$) comes from the NMC experiment, which observes only the logarithmic Q^2 dependence predicted by perturbative QCD [4]. The lack of evidence for strong Q^2 dependence of shadowing suggests that the conventional modeling of shadowing as a change in parton distribution functions is appropriate in the NuTeV kinematic region [5]. Significant Q^2 dependence is observed in charged-lepton scattering at low Q^2, but in a region irrelevant for NuTeV.

Miller and Thomas do not supply a theoretical framework for evaluating the impact of the model on the NuTeV results, nor are their estimates relevant for the NuTeV kinematics (the mean NuTeV Q^2 is $25.6\,{\rm GeV}^2$ for ν events and $15.4\,{\rm GeV}^2$ for $\overline{\nu}$ events). We attempt to apply their model by including the small effect of VMD neutral current shadowing and using the x dependence as given at 5 GeV^2 in Ref. [6], scaled with the above Q^2 dependence assuming $m_V=m_\rho$ (the lowest possible vector meson mass gives the maximum effect). We find that the predictions for $R^\nu_{\rm exp}$ and $R^{\overline{\nu}}_{\rm exp}$ increase by 0.6% and 1.2%, respectively. While these numbers are somewhat consistent with the ϵ and $\overline{\epsilon}$ values [7] which Miller and Thomas claim account for the entire NuTeV discrepancy, they neglect to include the high degree of correlation between the neutrino and antineutrino ratios in evaluating the effect on R^-. This brings us to the final point.

Differences in neutral and charged current shadowing will affect R^ν and $R^{\overline{\nu}}$ significantly. However, the NuTeV result derives $\sin^2\theta_W$ from the Paschos-Wolfenstein $R^-=(R^\nu-rR^{\overline{\nu}})/(1-r)$, where r is the ratio of $\overline{\nu}$ to ν charged current cross-sections ($r\approx 1/2$). This approach was chosen by NuTeV to limit sensitivity to suppression of charged current production of charm quarks from scattering on the strange sea, yet it is also equally effective at reducing sensitivity to other parts of the cross-section common to ν and $\overline{\nu}$, such as R_L or differences in neutral and charged current nuclear shadowing. A low x phenomenon like nuclear shadowing affects primarily sea quark cross-sections which contribute equally to ν and $\overline{\nu}$ cross-sections. For this reason, the ϵ and $\overline{\epsilon}$ parameters introduced in the comment [1] will be highly correlated, regardless of the specifics of the shadowing model, and will affect R^- only slightly. The NuTeV data themselves therefore rule out *any* such explanation because of the enormous shifts in R^ν and $R^{\overline{\nu}}$ individually required to induce a significant shift in R^-.

Even if we arbitrarily *increase* the effect of the VMD model in order to explain the NuTeV R^-, NuTeV's separate measurements of $R^\nu_{\rm exp}$ and $R^{\overline{\nu}}_{\rm exp}$ still cannot be accommodated. Defining $\Delta R = R_{\rm exp} - {R_{\rm exp}}^{\rm (SM)}$, NuTeV has measured:

$$\Delta R^\nu = -0.0032\pm0.0013 = R^\nu_{\rm exp}\times(0.9919\pm0.0033),$$
$$\Delta R^{\overline{\nu}} = -0.0016\pm0.0028 = R^{\overline{\nu}}_{\rm exp}\times(0.9960\pm0.0069),$$

with a correlation coefficient between the uncertainties of 0.638. This VMD model would therefore increase the discrepancy in $R^\nu_{\rm exp}$ from 2.5 to 4.5 standard deviations and in $R^{\overline{\nu}}_{\rm exp}$ from 0.6 to 2.3 standard deviations, and clearly a larger effect would be more disfavored. Also, note that the VMD model predicts the largest change in $R^{\overline{\nu}}_{\rm exp}$ whereas NuTeV observes a discrepancy primarily in $R^\nu_{\rm exp}$.

In conclusion, the VMD mechanism used in this comment [1] to motivate the possibility of a large difference in neutral and charged current shadowing is not motivated by charged lepton DIS data in the NuTeV kinematic region, and would have a smaller effect on the NuTeV measurement than is stated. Furthermore, VMD shadowing of sufficient size to explain the NuTeV $\sin^2\theta_W$ is conclusively excluded due to inconsistency with the NuTeV data itself. More generally, because any model of different neutral and charged current nuclear shadowing will change $R^\nu_{\rm exp}$ and $R^{\overline{\nu}}_{\rm exp}$ more than R^-, it is unlikely that any such model could explain the discrepancy in NuTeV's measurement of $\sin^2\theta_W$.

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[1] G. A. Miller and A. W. Thomas, hep-ex/0204007, April 2002.

[2] W. Melnitchouk and A. W. Thomas, Phys. Rev. **C52**, 3373 (1995).

[3] In VMD models, the effect on Z^0 exchange, as a fraction of the cross-section, is about $1/3$ of that in $W^\pm$ exchange, which is in turn about $1/2$ of that in γ exchange.

[4] M. Arneodo *et al.*, [NMC Collaboration], Nucl. Phys. **B487**, 3 (1997) , Nucl. Phys. **B481**, 23 (1996) .

[5] J. Kwiecinski and B. Badelek, Phys. Lett. **B208**, 508 (1988), B. Balelek and J. Kwiecinski, Nucl. Phys. **B370**, 278 (1992), N. N. Nikolaev and B. G. Zakharov, Zeit. Phys. **C49**, 607 (1991).

[6] C. Boros *et al.*, Phys. Rev. **D59**, 074021 (1999).

[7] As defined in the comment [1], $\epsilon = \delta R^\nu/R^\nu$ and $\overline{\epsilon} = \delta R^{\overline{\nu}}/R^{\overline{\nu}}$.